MEDIUM-DUTY URBAN RANGE EXTENDED CONNECTED POWERTRAIN

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Robert Bosch LLC

2018 DOE VTO Annual Merit Review

June 20th, 2017

Project ID #**ELT190 (GI190)**

This presentation does not contain any proprietary, confidential, or otherwise restricted information

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ELT190: MURECP Class 4 Delivery PHEV
Overview

Timeline

- Project start date = 8/19/2016
- Project end date = 11/30/2019
- Percent complete = 55%

Barriers

- **Performance** – 50% Fuel Consumption Reduction for class 4 delivery truck
  - Baseline = 8.5 MPG, Target >17 MPG
  - Full performance capabilities meeting or exceeding baseline vehicle
- **Cost** - < 3 year payback period
- **EV Range** - > 35 miles all electric range

Budget

- Total project funding
  - DOE share = $4,731,884
  - Contractor share = $1,984,907
- Funding received in FY 2017
  - $2,345,136
- Funding for FY 2018
  - $1,820,150

Partners

- Bosch – Project Lead
- Morgan Olson
- Voss Automotive, Inc.
- University of Michigan
- NREL
- Ricardo (vendor)

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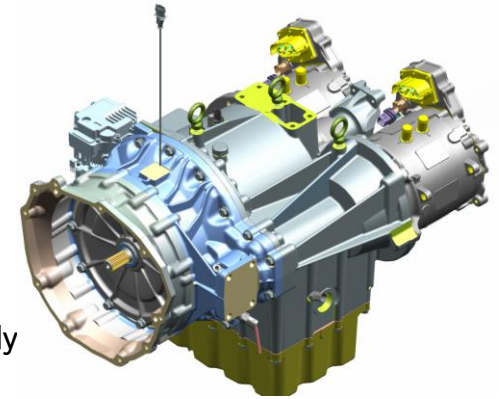
ELT190: MURECP Class 4 Delivery PHEV
Relevance/Project Objectives

- Demonstrate 50% fuel consumption reduction on CSHVC* utilizing a PHEV powertrain with a dual-planetary gear transmission via deep integration of electric components based on high-volume light duty vehicles
- Targets for May ’17-April ‘18:
  - Final transmission design selection (based on top 3 design finalists)
  - **Detailed Transmission Design and Hardware Procurement**
  - Develop control-oriented transmission models
  - **BP1 Go/No-Go: 50% target achieved via high fidelity simulation**
  - VCU/ECU SW Development
  - PHEV System Design Freeze and 3D CAD Chassis Packaging Study



- Evaluation against Project Barriers
  - **Performance:** current simulation modeling predicts ~18.5 MPG (~57% fuel consumption reduction) on CSHVC* in charge sustaining mode
    - >20 million gallons of diesel fuel saved per year class 4, >55 million gallons per year class 3-5
  - **Cost:** target ROI <3 years (Simple Pay-back)
    - ~3.2 years ROI with 2018 costs, HEV battery size (20 kW-hr), and 39k miles/year
    - ~2 years ROI with 2022 costs as PHEV w/ 60 mile EV range and 39k miles/year
  - **EV Range:** ~60 miles of all-electric range achievable with existing battery packs on the CSHVC* based on 2x 24 kW-hr packs in parallel

*CSHVC=City Suburban Heavy Vehicle Cycle

ELT190: MURECP Class 4 Delivery PHEV
Milestones FY 2017

*CSHVC=City Suburban Heavy Vehicle Cycle

Milestone	Type	Description	Date	Result
Validated baseline simulation model	Technical	Simulation baseline model fuel consumption prediction within 10% of baseline vehicle measurement results	12/31/2016 ☑	GT Suite model predicted 8.2 MPG on CSHVC* compared to NREL's chassis dyno data of 8.5 MPG
Validation of dual-planetary gear hybrid powertrain	Technical	Quantify superior benefits of the 2PG hybrid powertrain as compared to other architectures	2/25/2017 ☑	P2 Hybrid with downsized internal combustion engine achieved 39% fuel consumption reduction vs. 2PG Power-split hybrid achieving 60% fuel consumption reduction (CSHVC*, Charge Sustaining)
Defined hybrid powertrain topology and components	Technical	Component selection for the proposed solution to achieve the desired fuel consumption reduction and cost target	7/17/2017 ☑	Final topology selected- Design 698b. Components defined.
Developed control-oriented transmission models	Technical	The control-oriented models will be simple to implement while capturing the primary transmission dynamics	8/21/2017 ☑	Rule-based control development completed. System optimal controller implemented, showing additional FC reduction potential.
Powertrain Architecture Defined	Go/No Go	Modeling results show the architecture can achieve a 50% reduction in fuel consumption	11/30/2017 ☑	Achieved. >50% fuel consumption reduction in charge sustaining mode on CSHVC. >90% reduction in charge depletion mode (uncorrected)

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Milestones FY 2018

Milestone	Type	Description	Date	Result
Validated supervisory controller with hybrid configuration	Technical	Supervisory controller validation in GT-SUITE is completed and produces preliminary fuel economy results	10/31/2018 ☐	Rule Based Eng. Optimal Completed- Jan. 2017 Rule Based Sys. Optimal Completed- Aug. 2017 Mode Switch Controller- May 2018 Diagnostic/Limp Home- Oct. 2018
Completed 3D CAD model of the final design solution	Technical	Virtual packaging study completed in the vehicle space and installation locations for all new components defined	6/30/2018 ☐	On-going: Morgan Olson has received all component CAD models and begun virtual placement. Initial priority upon thermal system, second upon HV components.
Finalized driveline design	Technical	The hybrid drive system design, integration, and optimization will include an optimum final drive ratio(s)	4/30/2018 ☑	Completed. With large tires (~480mm RR) a 4.78:1 FDR is defined. For smaller/normal tires (~400mm RR) a 3.91:1 FDR is defined.
GEM "certification" via powertrain test procedure	Technical	Powertrain mapping procedure completed with input maps used to generate a GEM vehicle certification CO2 /fuel consumption values	11/30/2018 ☐	On-schedule- awaiting powertrain dyno test results starting in July 2018.
Rolling chassis operational under its own power	Go/No Go	Class 4 PHEV delivery truck is assembled and basic drive functionality is demonstrated	11/30/2018 ☐	On-schedule- awaiting final chassis + body delivery.

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ELT190: MURECP Class 4 Delivery PHEV
Milestones FY 2019

Milestone	Type	Description
Steering committee ride-and- drive approval granted	Technical	After powertrain and vehicle calibration work is completed, steering committee will provide ride-and-drive sign-off
Completed chassis dynamometer fuel consumption testing	Technical	Chassis Dyno testing at NREL completed to validate achievement of a 50% fuel consumption reduction
Completed limited real-world driving cycle fuel consumption testing	Technical	In-use testing of fuel consumption and emissions conducted to validate achievement of a 50% fuel consumption reduction for a given drive cycle
In-use fuel consumption determined	Technical	Quantify the fuel consumption reduction during a fleet demonstration of for a real-world driving cycle

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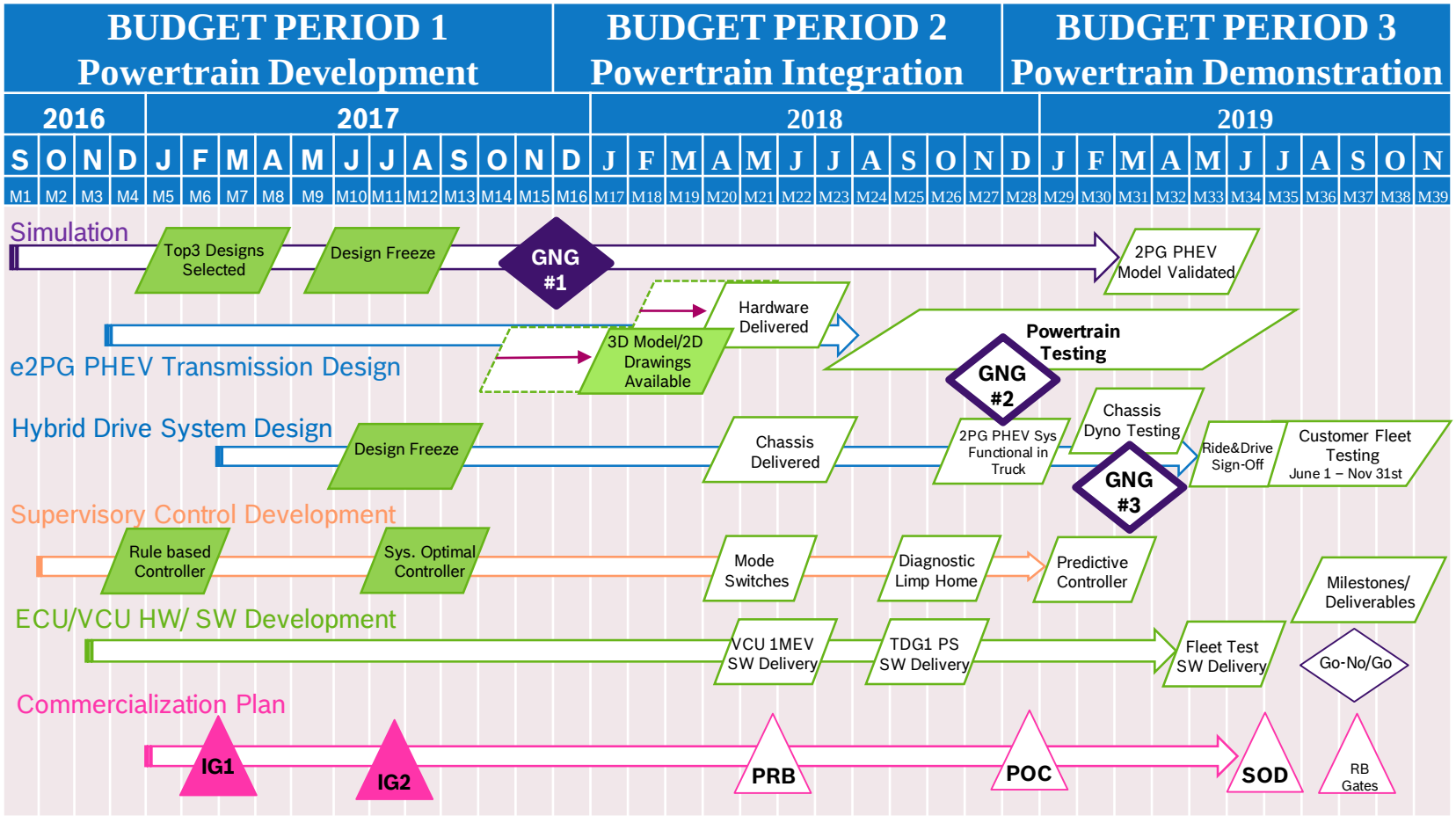
Approach- Overview (Full Project View)



**POC = Proof of Concept
***SOD = Start of Development

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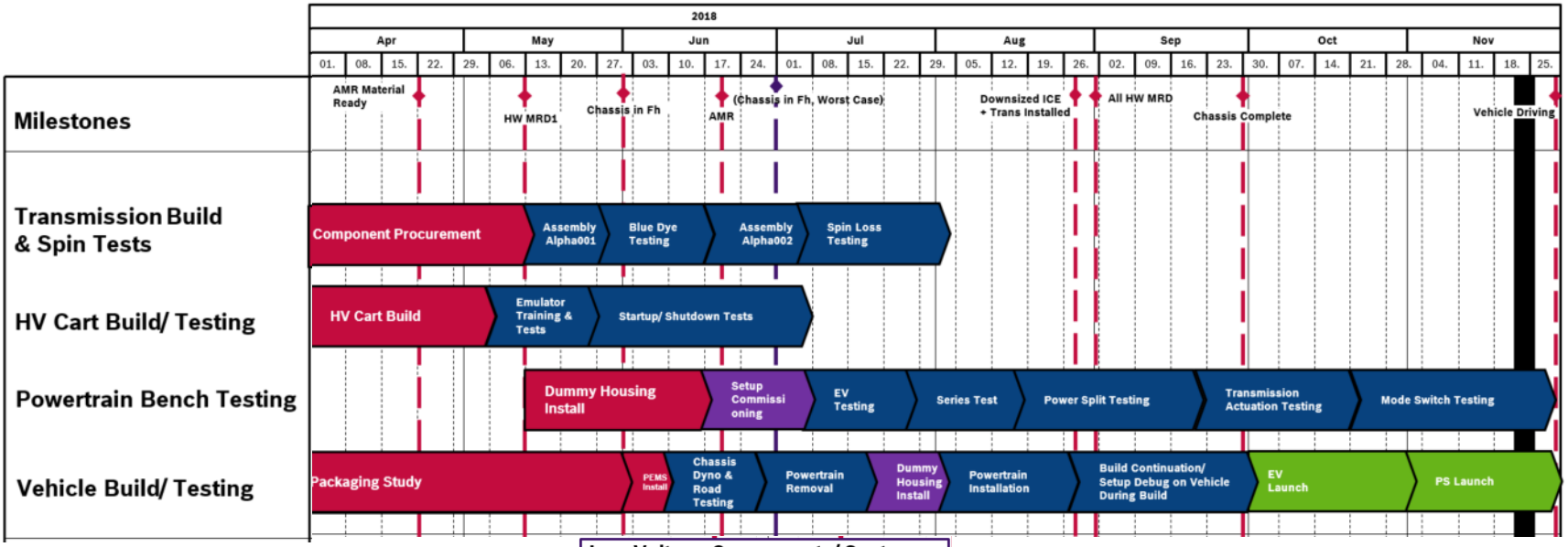
ELT190: MURECP Class 4 Delivery PHEV
Approach- Detailed (BP2 View)



High Voltage Components/ Systems
INVCON3.3 (2x) Install
HV Battery Pack Install (2x)
HV PTC Heater (Coolant for cabin heat)
HV/24V DC/DC Converter
On-Board Charger
A/C Compressor & Water/Refrigerant Chiller
PDU (Power Distribution Unit)

Low Voltage Components/ Systems
Body & Powertrain Removal + Body Install
VM 3.0l Prep + Trans Mount Design + Trans Install
Power Steering System- Drain/Prep
Power Steering System- Install Electro-Hydraulic Pumps (2)
Thermal System (Pumps/Valves)
PHEV Radiator/Fans Install + Coolant Fill
Engine Controller/ Vehicle Controller/ Multi-Pack Controller
Steel Fuel Tank Drain/ Removal
Electric Fuel Pump/ Tank Order + Install
12V Batteries Order + Install
PRNDL Rotary Knob- Dash Mount
DDU10 (Driver Display Unit)
Coolant Lines/ Connectors
Aftertreatment System Removal + Install
Measurement equipment install
Drive Shaft Order + Adaption (hand brake + 1st shaft)

Wire Harnesses
LV 'Lay-In' Harness Build
HV Cable Termination in PDU

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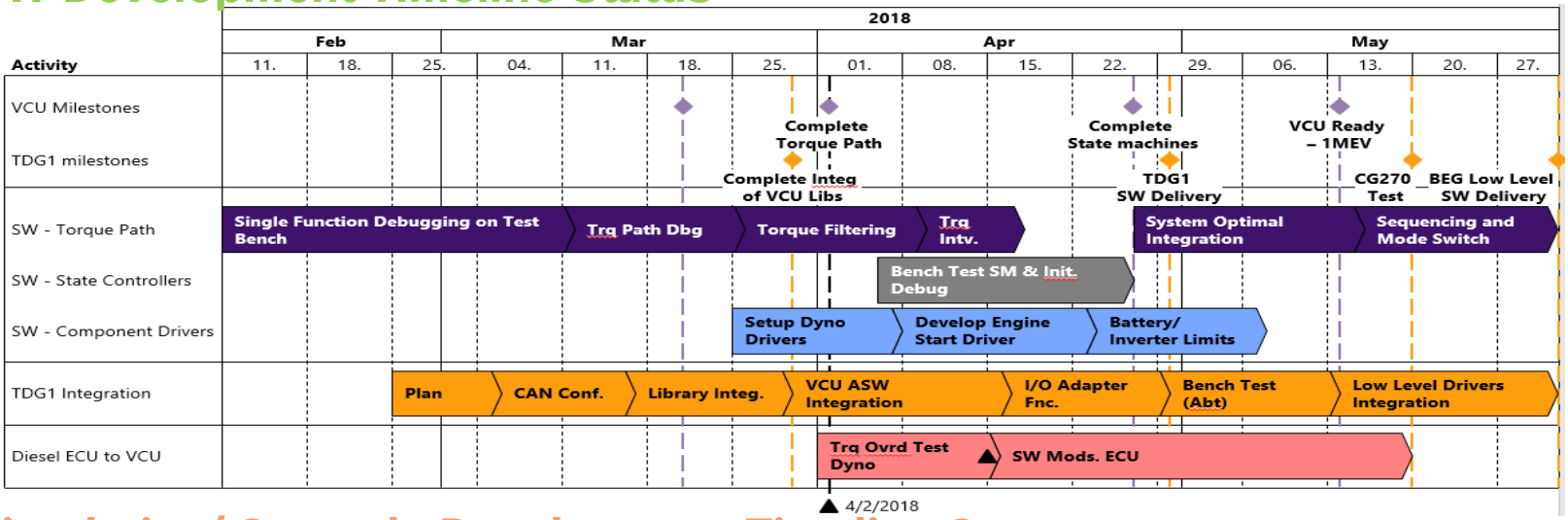
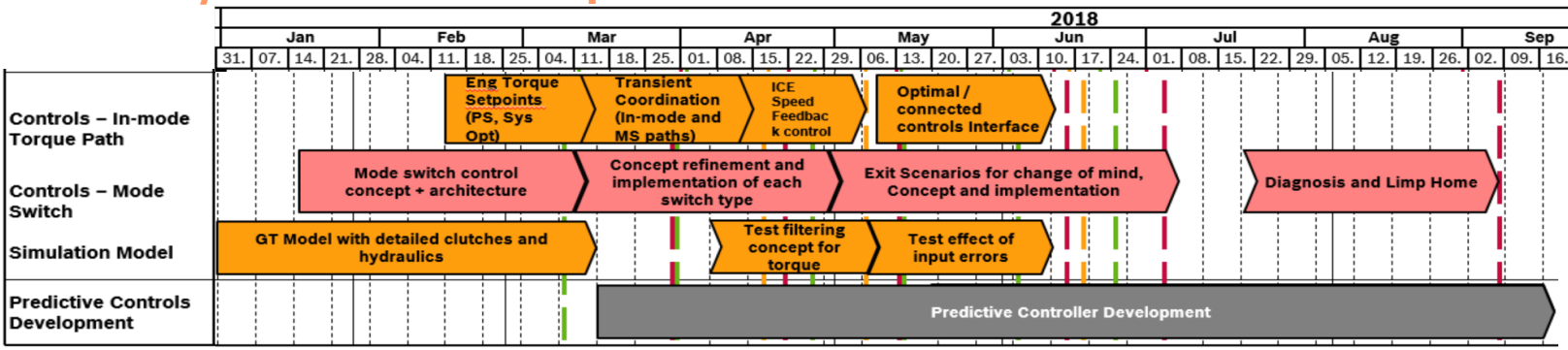
Approach- Detailed (BP2 View)

SW Development Timeline Status



Simulation/ Controls Development Timeline Status



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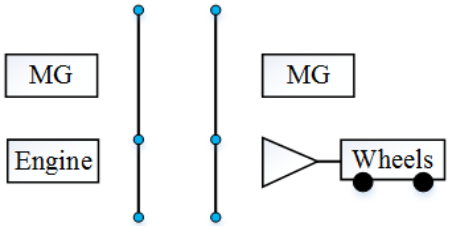
Technical Accomplishments and Progress

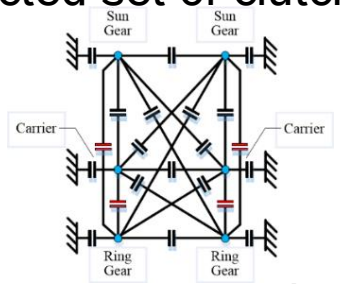
Powertrain Architecture Evaluation Procedure

- Configuration: collocation of components given a topology
  - 2 planetary gearsets w/ 6 Nodes
  - 3 input and 1 output components



$$\frac{1}{2}P_6^4 = 180$$

- Design: a configuration plus a selected set of clutches
  - 15 rotating/ 6 braked clutched locations possible



$$\frac{1}{2}P_6^4 \cdot C_{15}^3 = 180 \cdot 455 = 81{,}900$$

- Design Candidate: Considering 3 beta ratios and 5 final drive ratios

$$81{,}900 \cdot 3 \cdot 3 \cdot 5 \cdot 5 = 18{,}427{,}500$$

Credits to UofM Prof. Peng and PhD Candidate Ziheng Pan

Transmission Design Down-Select Algorithms enable efficient modeling and screening of >81,000 designs

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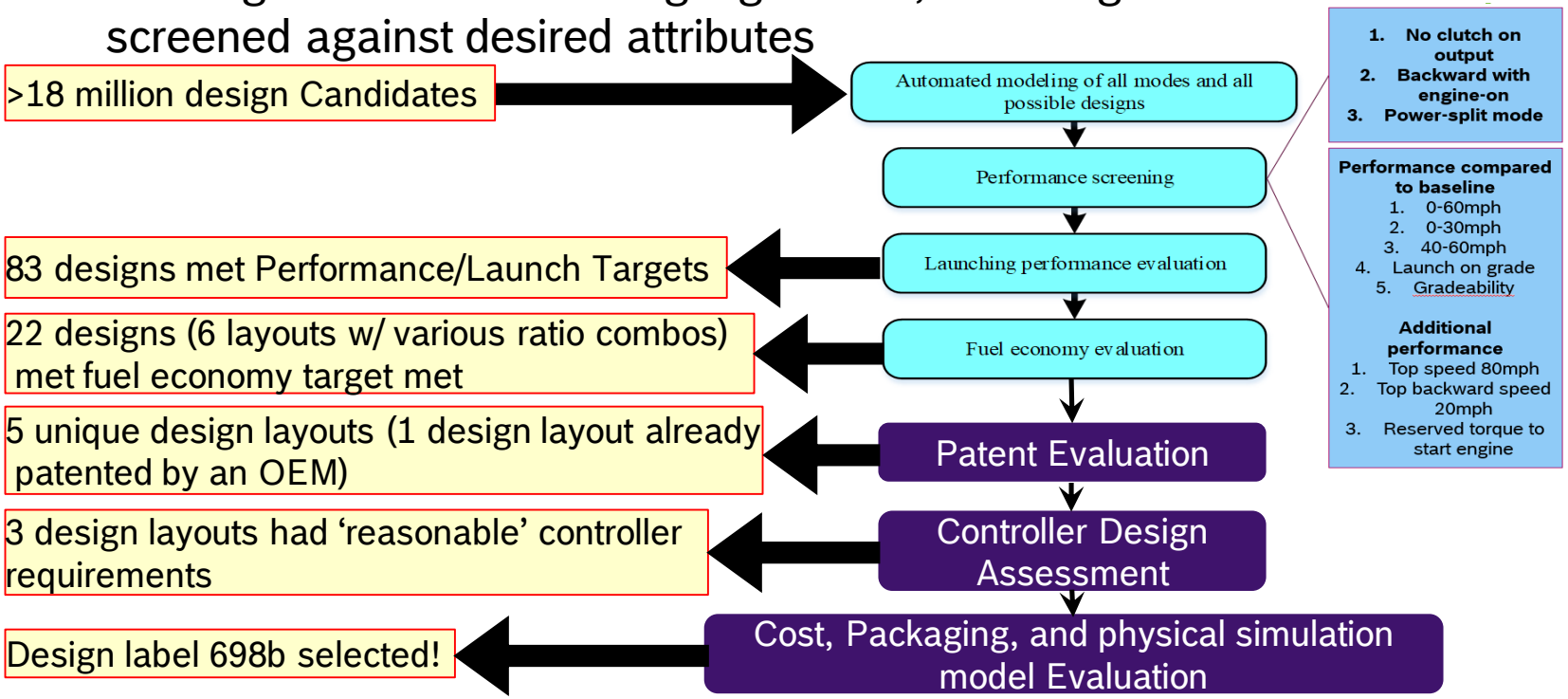
Technical Accomplishments and Progress

Powertrain Architecture Evaluation Procedure

- Utilizing automated modeling algorithms, the design candidates were screened against desired attributes



Design label 698b was selected, as it was estimated to have the lowest fuel consumption, lowest cost/weight/size, and simplest controller design. Best of all worlds!

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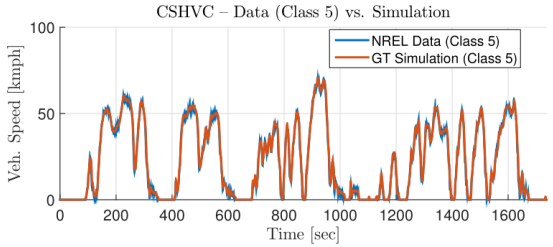
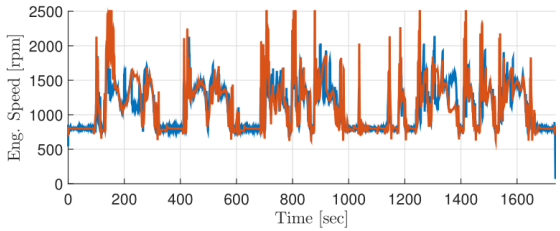
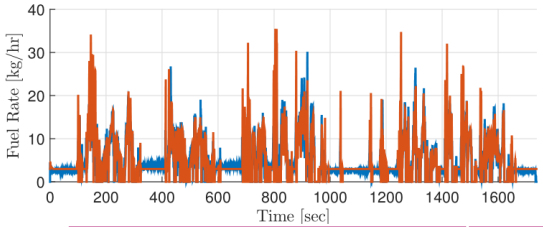
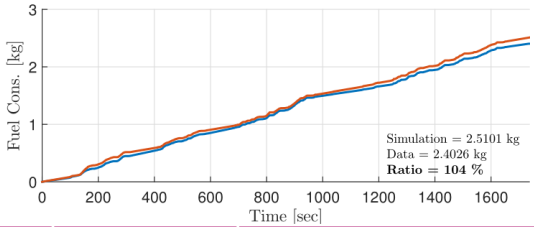
Technical Accomplishments and Progress









2403 g
0.756 gal
8.9 MPG

	Initial Model	Updates	MURECP Targets
Vehicle Weight [lb.]	16,000 lb.	15,410	16,000
Aerodyanmics: CdA [m2]	5.4	4.36	4.36
Rolling Resistance [-]	0.00738	0.0071	0.0071
Tire Radius [mm]	480mm	420 mm	420 mm/ 480mm
Start/ Stop	No	No	Yes
Final Drive Ratio	4.3	4.3	3.91/ 4.78

Baseline Truck, as measured on chassis dyno, had a Fuel Economy of 8.9 MPG. New correlation re-achieved w/ updated vehicle parameters.

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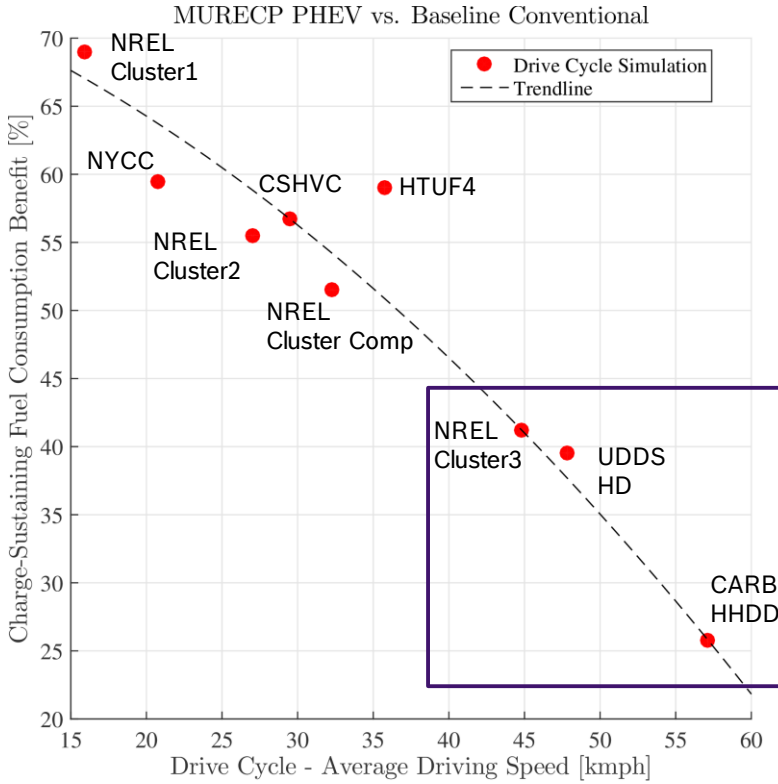
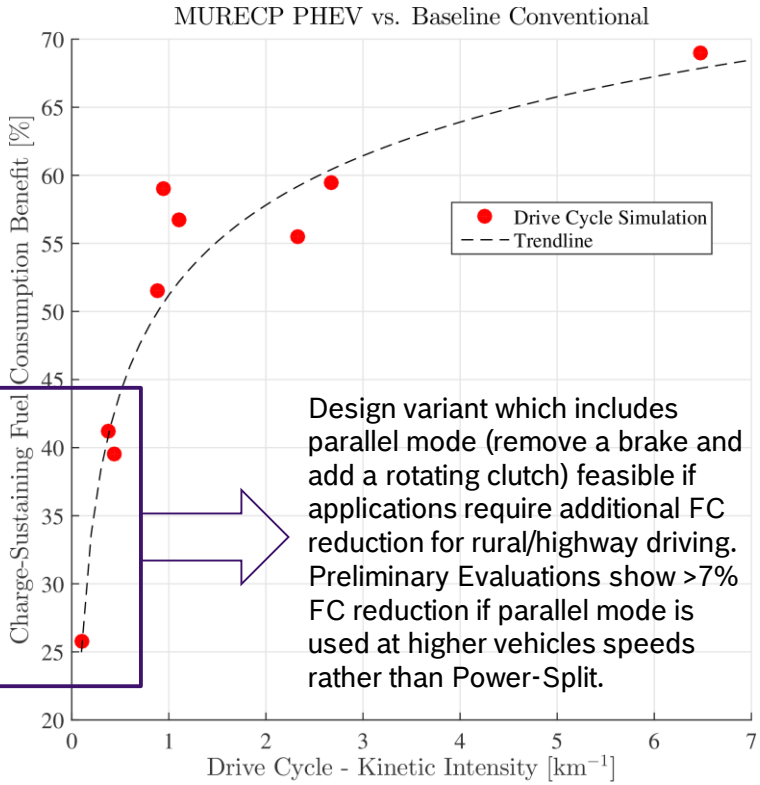
Technical Accomplishments and Progress



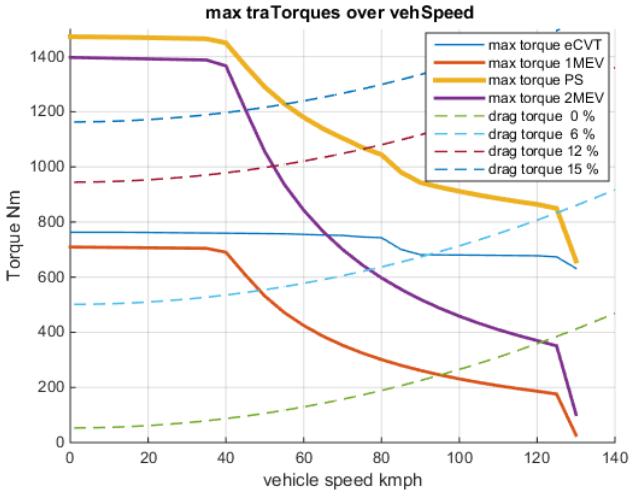


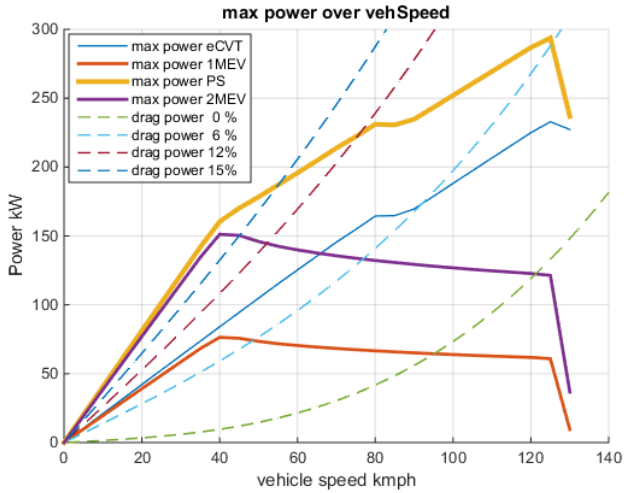
Design variant which includes parallel mode (remove a brake and add a rotating clutch) feasible if applications require additional FC reduction for rural/highway driving. Preliminary Evaluations show >7% FC reduction if parallel mode is used at higher vehicles speeds rather than Power-Split.

Strategy: Start at 25% SOC. Aim to end at 25% SOC. Fuel consumption results correct for any deviation in final SOC vs. target SOC.

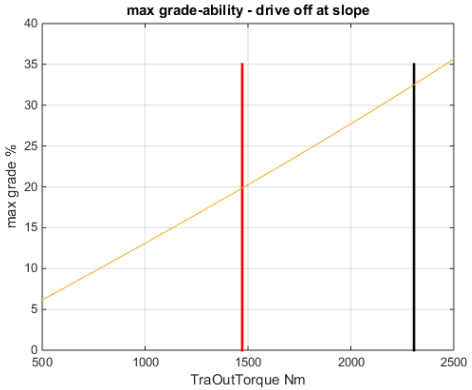
>50% fuel consumption reduction target (in charge-sustaining mode) met for drive cycles with <37 kmph average speed or >0.9 1/km KI

ELT190: MURECP Class 4 Delivery PHEV
Technical Accomplishments and Progress





- 20% grade on launch possible in EV and PS modes
- Up to 50 km/h on 15% grade
- >120 km/h on 6% grade



- >120 km/h on 0% grade in 2 Motor EV mode is possible
- ~130 km/h on 6% grade in PS mode is possible
- ~55 km/h (35 mph) possible in 2 motor EV mode on 12% grade

*PS- Powersplit

Performance and Grade-ability Targets met!

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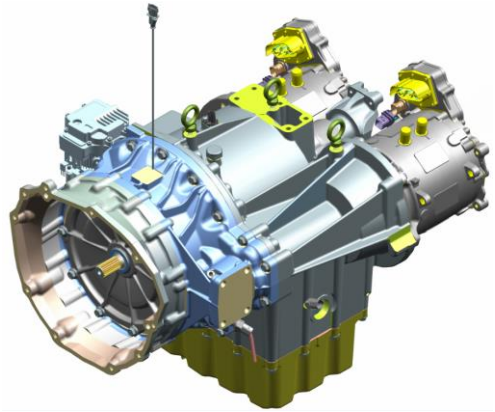
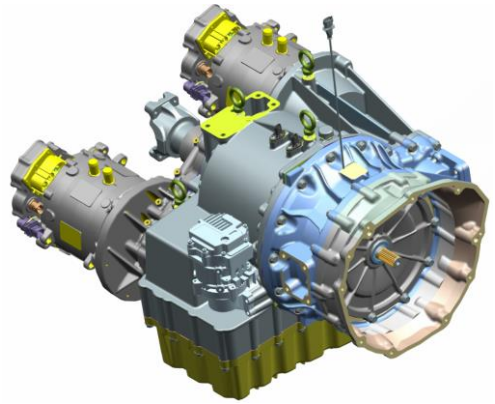
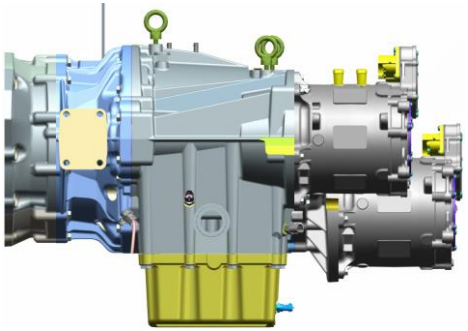
ELT190: MURECP Class 4 Delivery PHEV
Technical Accomplishments and Progress

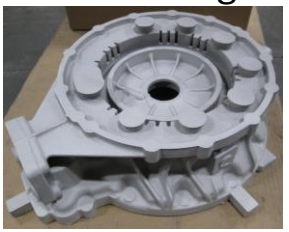






Adapter Housing

Front Housing



Main Housing

Oil Pan

Valve Body (3 pieces)

Transmission Design Completed- First Sample Available May 28th, 2018

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Technical Accomplishments and Progress

Costs @ 39k Miles/year Diesel Fuel= $2.95/gal Charge Sustaining	Scenario1- 2015 PHEV	Scenario3a- HEV Battery Size	Scenario3b- HEV Battery Size + 2022 BAT costs	Scenario3c- HEV Battery Size + 2022 costs	
Motor + Inverter	30	30	30	**8**	$/kW
	160	160	160	160	kW
	4800	4800	4800	1280	$
Battery Pack	300	300	**125**	**125**	$/kWh
	48	**20**	**20**	**20**	kWh
	14400	6000	2500	2500	$
e2PG PHEV Add-on Cost **(2x OEM Markup)**	$38,400.00	$21,600.00	$14,600.00	$7,560.00	$
Savings					
Fuel Savings 50% FC Reduction	$6,767.65	$6,767.65	$6,767.65	$6,767.65	$
Payback Period	5.67	3.19	2.16	1.12	Years
Fuel Savings 55% FC Reduction	$7,480.03	$7,480.03	$7,480.03	$7,480.03	$
Payback Period	5.13	2.89	1.95	1.01	Years

Battery Cost Targets https://www.energy.gov/sites/prod/files/2017/06/f34/67089_EERE_LIB_cost_vs_price_metrics_r9_0.pdf

eDrive Cost Targets https://www.energy.gov/sites/prod/files/2017/03/f34/QTR2015-8E-Plugin-Electric-Vehicles-15Mar2017.pdf

Assuming a small 'HEV' battery size of 20 kW-hr an attractive ROI (Simple Payback) of ~3.2 years can be achieved w/ 2018 Costs!

ELT190: MURECP Class 4 Delivery PHEV
Technical Accomplishments and Progress

Costs @ 26k Miles/year Diesel Fuel= $2.95/gal Charge Depletion -60 miles EV/day	Scenario1- 2018 PHEV	Scenario2a- 2022 Battery	Scenario2b- 2022 Battery + eDrive	
Motor + Inverter	30	30	**8**	$/kW
	160	160	160	kW
	4800	4800	1280	$
Battery Pack	300	**125**	**125**	$/kWh
	48	48	48	kWh
	14400	6000	6000	$
e2PG PHEV Add-on Cost **(2x OEM Markup)**	$38,400.00	$21,600.00	$14,560.00	$
Savings				
Fuel Savings 50% FC Reduction	$7,218.82	$7,218.82	$7,218.82	$
Payback Period	5.32	2.99	2.02	Years
Fuel Savings 55% FC Reduction	$7,408.79	$7,408.79	$7,408.79	$
Payback Period	5.18	2.92	1.97	Years

Customer Fleet info:
~100-200 miles/day
5 days/ week
52 weeks/year

100 miles/day = 26k/year
150 miles/day = 39k/year
200 miles/day = 52k/year

Battery Cost Targets https://www.energy.gov/sites/prod/files/2017/06/f34/67089_EERE_LIB_cost_vs_price_metrics_r9_0.pdf
eDrive Cost Targets https://www.energy.gov/sites/prod/files/2017/03/f34/QTR2015-8E-Plugin-Electric-Vehicles-15Mar2017.pdf

Assuming a PHEV battery size of 48 kW-hr an attractive ROI (Simple Payback) of ~1.5 years can be achieved w/ 2022 Cost Targets!

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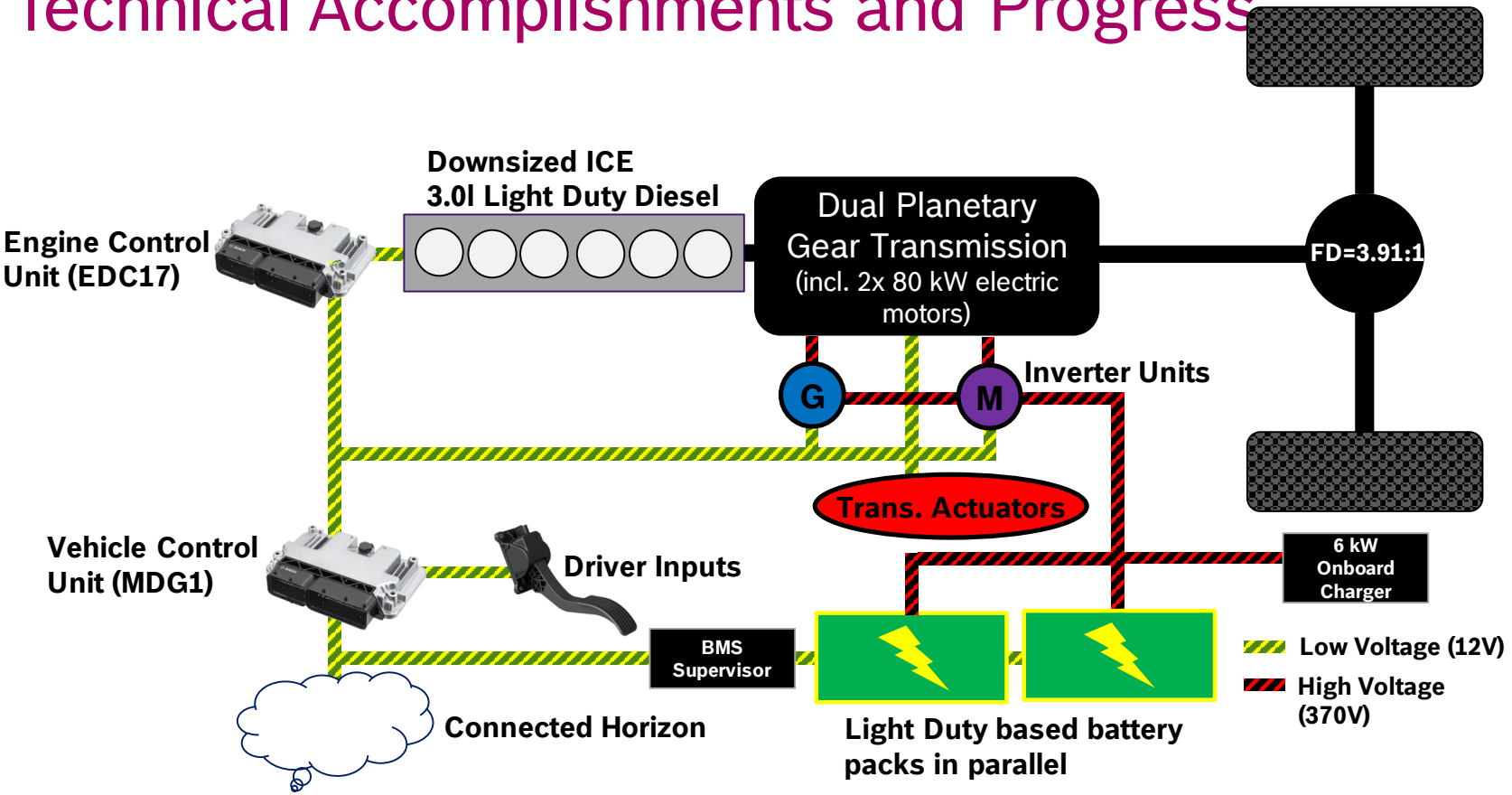
Technical Accomplishments and Progress



Dual-planetary gear PHEV system architecture defined

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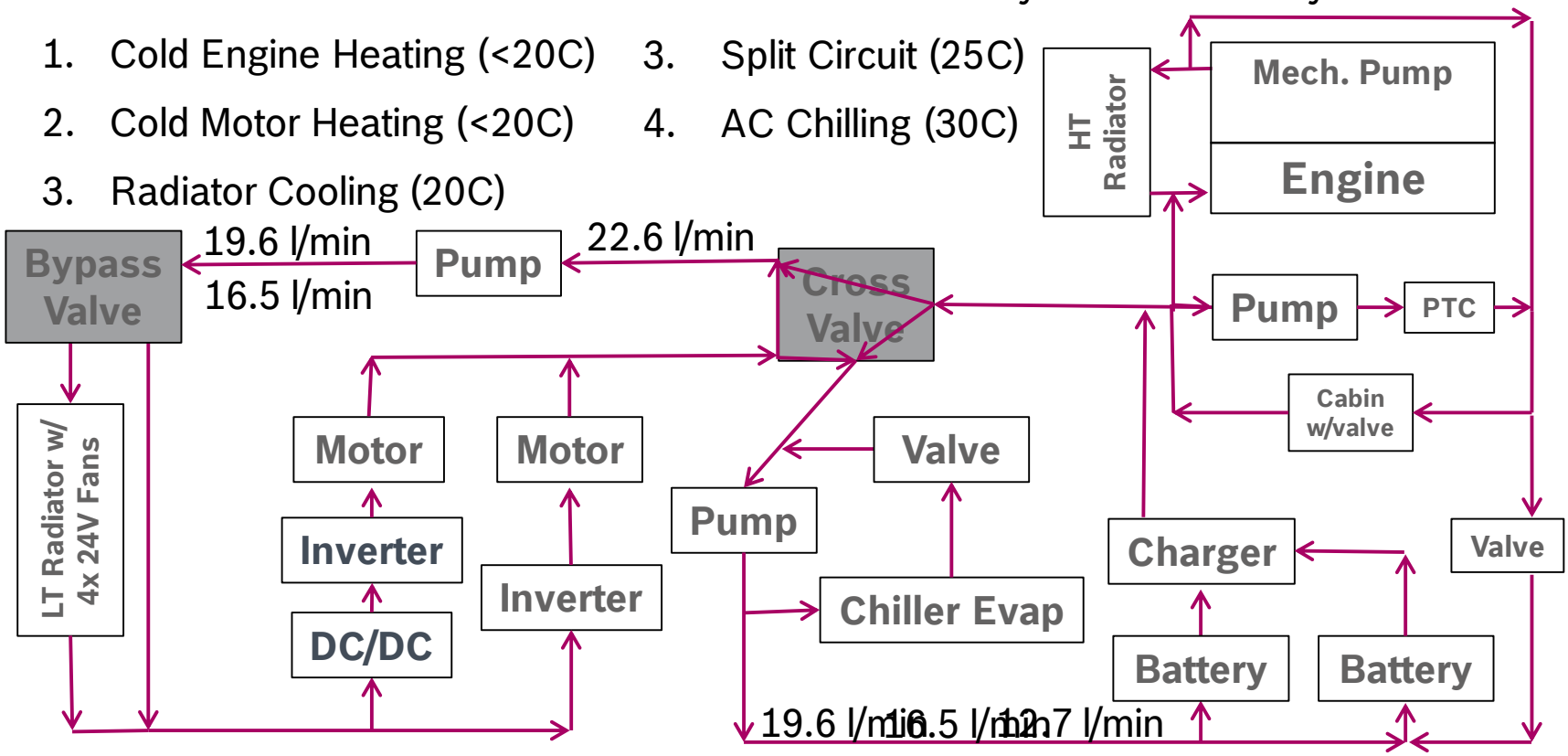
Technical Accomplishments and Progress

Full Circuit

Grey valves thermally actuated

1. Cold Engine Heating (<20C)
2. Cold Motor Heating (<20C)
3. Radiator Cooling (20C)
3. Split Circuit (25C)
4. AC Chilling (30C)



Thermal System Layout Defined by VOSS Automotive. SW Integration Ongoing.

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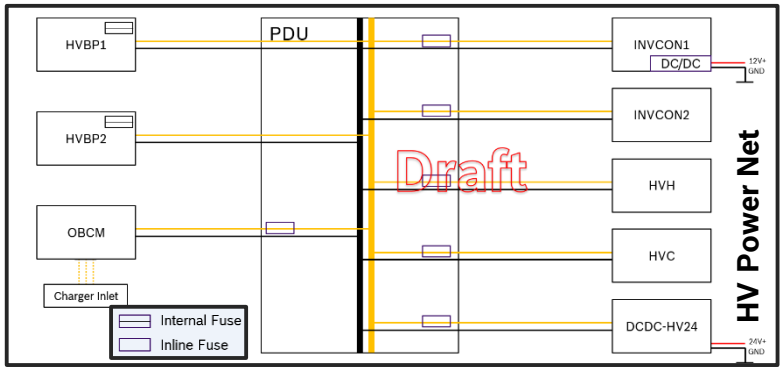
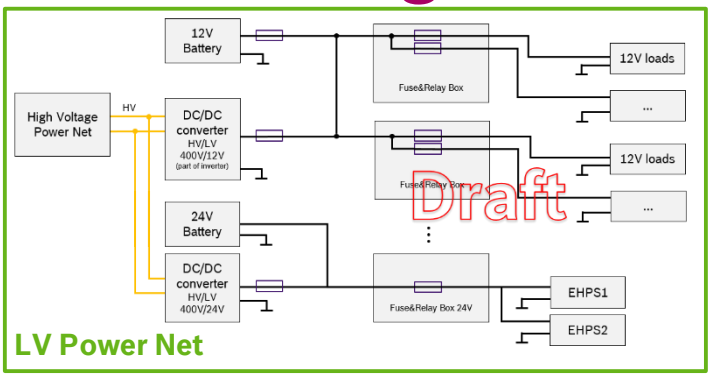
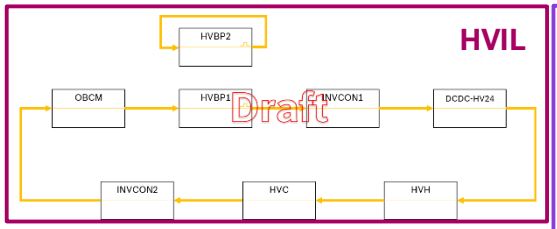
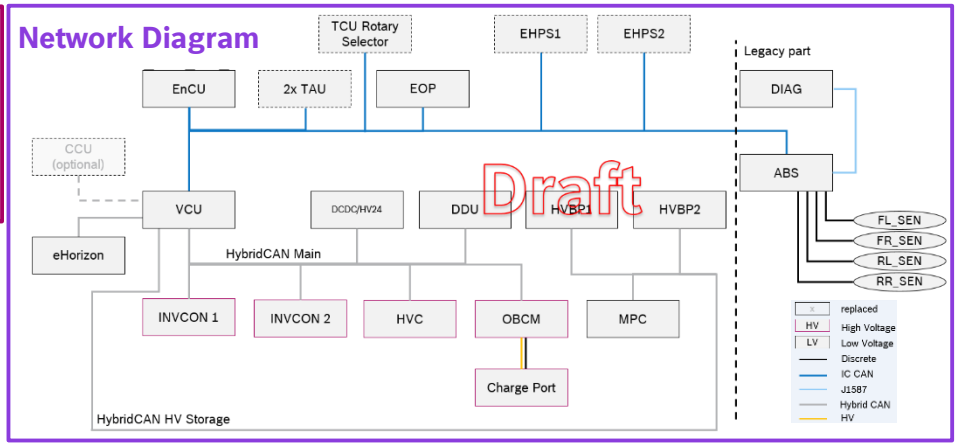
Technical Accomplishments and Progress









Electrical/ Electronic Architecture definition on-going. Key open points surrounding the 24V power net and PDU design.

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ELT190: MURECP Class 4 Delivery PHEV
Responses to Reviewers' Comments (Top 3)

Reviewer Comments	Response	Further Action?
Baseline MPG too low	Based on the measurement data available, both from chassis dyno and field testing, 8.9 MPG is correct for a 2011 FedEx vehicle on the CSHVC.	Further measurements on a 2017 Freightliner MT45 planned for May/June 2018.
Cost targets unclear/ not considered in down-select process	Cost target for the PHEV system add on costs (e2PG, battery, eDrives) is to enable a <3 year payback period. Costs were considered in the final design selection, where the chosen design had the lowest estimated system costs.	None.
Further out-reach possible, testing w/ additional fuel sources	-Team is currently reaching out to potential transmission manufacturing partners and OEMs. Target is to have commercialization plan finalized by E. 2018. -Simulations on-going for different vehicle types/ applications.	Conduct simulations until end of BP2 with 1 gasoline engine and 1 natural gas engine. Based on results an evaluation can be made to conduct further testing.

ELT190: MURECP Class 4 Delivery PHEV
Collaboration with Other Institutions

Organization	Role	Responsibilities
Robert Bosch LLC	Project Lead	Technical project management, downsized engine calibration Vehicle calibration, monitoring strategy support DPF regen and SCR dosing strategy calibration Engine ECU SW modifications for PHEV Design, manufacturing, and interface support of electric motors and inverters Powertrain and controls simulation and calibration, electronic horizon calibration Battery management system, powertrain architecture optimization, controls R&D
University of Michigan	Partner	Powertrain architecture optimization, controls R&D, eHorizon evaluation @ Mcity
Morgan Olson	Partner	Vehicle integration, vehicle fleet testing, consulting
VOSS Automotive	Partner	Thermal management system design, build, integration
NREL	Partner	Vehicle fuel economy validation, drive-cycle definition, cost-benefit ratio analysis, chassis dynamometer testing, field evaluation
Ricardo	Vendor	Transmission design, manufacturing, and interface support
Freightliner Custom Chassis Corp.	Support	Base chassis information support, including CAD models and wiring diagrams

ELT190: MURECP Class 4 Delivery PHEV
Collaboration with Other Institutions

Organization	Role	Responsibilities
ZF	Support/ Vendor	Powertrain testing support (conventional PT w/ 8 sp. Auto trans), Torsional Damper Design and Supply
FCA	Support	Engine interface support, wire harness diagrams
Modine	Vendor	LT Radiator/Cooling System Package Design and Supply AC/Coolant Chiller Supplier
FZB	Vendor	Electro-Hydraulic Power Steering System Design and Supply
Brusa/ Metric Mind	Vendor	HV/24V DC/DC Converter Supplier
Currentways	Vendor	On-Board Charger Module Supplier
Sanden	Vendor	HV A/C Compressor Supplier

ELT190: MURECP Class 4 Delivery PHEV
Remaining Challenges and Future Research

Key Challenges

- Determine optimum battery sizing
  Range ↑ / Size, Weight, and Cost ↓
- Developing and manufacturing a dual planetary gear transmission w/ plug-in electric motors (PC based) for class 4 CV trucks, which is scalable within classes 2b-8a
- Achievement of system cost targets and payback period
- Packaging of PHEV system into existing chassis

Future Research

BP2 (April ’17 – November ’18)

- Delivery of 2 Transmission Samples
- Powertrain Testing
- Chassis Packaging Study
- Thermal System Design
- Electrical System Design
- Chassis Build & Basic Drive Functionality
- Commercialization Plan

BP3 (December ’18 – November ’19)

- Vehicle calibration
- Chassis Dyno Test
- 6 Month Customer Fleet Testing

ELT190: MURECP Class 4 Delivery PHEV

Summary

Simulation activities to-date indicate that our PHEV architecture w/ a dual planetary gear transmission will meet the project objective of >50% fuel consumption reduction on the City Suburban Heavy Vehicle Cycle (CSHVC*), even in charge sustaining mode

Features	Fuel Consumption % Improvement
Baseline Vehicle	-- (8.9 MPG)
Downsized Engine	22% (DP result)
Parallel Hybrid w/ downsized engine	39% (DP result)
HEV w/ Dual-Planetary Gear Transmission and 3 Clutches	57% (DP predicted 61%)
PHEV w/ Dual-Planetary Gear Trans. and 3 Clutches (EV only)	100% (55 MPGe**) 1.45 miles/kW-hr

*CSHVC = City Suburban Heavy Vehicle Cycle
Model Basis: GT-Suite w/ Optimized Rule-based controls
DP = Dynamic Programming (Matlab)

**6.68 miles on CSHVC
37.656 kW-h/gallon diesel fuel

Medium-Duty Urban Range Extended Connected Powertrain

THANK YOU! QUESTIONS?

P.I. – Alex Freitag, Director of Engineering, Powertrain Solutions- Commercial Vehicles

Presenter – Matt Thorington, Principal Engineer, Powertrain Solutions, Commercial Vehicle Electrification

Robert Bosch LLC

2018 DOE VTO Annual Merit Review

June 20th, 2017

Project ID #**ELT190 (GI190)**

This presentation does not contain any proprietary, confidential, or otherwise restricted information

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